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# APPLICATION

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TITLE: OPTICAL SPECTRUM MONITOR

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# OPTICAL SPECTRUM MONITOR

**[0001]** This application claims the benefit of U.S. Provisional Patent Application No. 60/441,112 of the same title filed on January 17, 2003, the disclosure of which is incorporated herein by reference as part of this application.

## Background

**[0002]** Optical signals may have optical spectral components at one or more wavelengths within the electromagnetic spectrum. Optical spectral components at different wavelengths may include useful information such as properties of a light source, an optical material, device or transmission media. In various applications, it may be desirable to analyze the optical spectral components of an optical signal.

## Summary

**[0003]** This application includes optical devices and techniques for monitoring spectral components in optical signals. Such devices and techniques can be used in a wide range of applications where the spectral information of light is important. For example, in fiber optical communication systems, it may be desirable to analyze and monitor WDM and DWDM channels at different channel wavelengths, or to obtain spectral information of a particular signal, such as a DWDM channel, to analyze dispersion effects in that signal.

[0004] In one implementation, for example, a spectrum monitoring device may include an input fiber to receive input light, an output fiber, a first fiber, a second fiber, and a fiber coupler. The fiber coupler has a first port coupled to the input fiber and the output fiber, and a second port coupled to the first and the second fibers to split the input light into a first beam in the first fiber and a second beam in the second fiber and to mix and couple optical signals from the first and the second fibers into the output fiber. This spectrum monitoring device in this implementation further includes a first reflector coupled to the first fiber to reflect the first beam back to the fiber coupler, and a second reflector coupled to the second fiber to reflect the second beam back to the fiber coupler. An optical detector is coupled to receive light from the output fiber to produce a detector output having information on optical interference between the first and the second beams received at the fiber coupler. An analog-to-digital converter is coupled to convert the detector output into a digital signal. This device further includes a processing device receiving and performing a FFT processing on the digital signal to extract spectral information in the input light. In addition, a fiber tuning mechanism may be coupled to at least one of the first and the second fibers to change a relative delay in the first and the beams upon reflection to back the fiber coupler.

**[0005]** In another implementation, a device may include an optical coupler to receive an input optical signal and to split the input optical signal into a first optical signal and a second optical signal, first and second optical paths, an optical detector, and a processing circuit. Each of the first and second optical paths receives the optical signal from the optical coupler and includes a reflector that reflects light back and makes polarization of reflected light to be orthogonal to polarization of light incident to the reflector prior to reflection. The optical detector is coupled to receive the optical output signal from the optical coupler and produces an electronic signal from the optical output signal. The processing circuit performs a fast Fourier transform on the electronic signal to extract spectral information in the input optical signal.

**[0006]** A method is also described as an example. In the described example, an input optical signal is split into first and second optical signals in first and second optical paths, respectively. Each of the first and second optical signals is reflected back with polarization in reflection to be orthogonal to polarization of light prior to reflection. The reflected first and second optical signals are spatially overlapped to interfere with each other to produce a mixed output optical signal which is converted into an electronic signal. A fast

Fourier transform (FFT) is applied on the electronic signal to extract spectral information in the input optical signal.

**[0007]** These and other implementations and variations are describe in greater detail with reference to the drawings, the detailed description, and the claims.

## Brief Description of the Drawings

**[0008]** FIG. 1 shows one exemplary design of a spectral monitoring device based on optical interference and FFT processing.

**[0009]** FIG. 2 illustrates an exemplary implementation of a spectral monitoring device based on the design in FIG. 1.

## Detailed Description

**[0010]** FIG. 1 shows one implementation of a polarization-insensitive spectrum monitoring device 100 based on a Michaelson interferometer mechanism. The device 100 uses an input fiber 101 to receive input light under measurement. A fiber coupler 110, such as a 50% (3dB) fiber coupler, is coupled to the input fiber 101 and an output fiber 150 on one end and is also coupled to two fibers 111 and 112 on the other end. Hence, the input light in the input fiber 101 is split between the fibers 111 and 112. The light beams received from the fibers 111 and 112 are coupled and mixed by the coupler 110. One portion of the mixed light is sent out to the output fiber 150 and the remaining portion to the input fiber 101. As illustrated, an optical isolator 104 may be coupled in the fiber 104 to eliminate the optical feedback to the input fiber 101.

**[0011]** The device 100 implements the Michaelson interferometer mechanism by coupling two optical reflectors 141 and 142 at the ends of the fibers 111 and 112, respectively. Hence, light beams received by the fibers 111 and 112 from the coupler 110 by splitting the input beam in the fiber 101 are reflected back by the reflectors 141, and 142, respectively. As long as the difference in the optical path lengths of the reflected beams is within the coherent length of the original input light in the fiber 101, the reflected beams, upon mixing by the coupler 110,

interfere with each other so that the output beam in the fiber 150 has the interference information. This configuration is similar to the two-arm Michaelson interferometer.

[0012] Notably, each of the two reflectors 141 and 142 may be configured as a Faraday reflector by including a Faraday rotator in front of an optical reflector such as a mirror. Hence, the polarization of the reflected light is orthogonal to the polarization of the incident light to the reflector prior to the reflection. In operation, for example, this Faraday reflector operates to rotate the polarization of reflected light by 90 degrees with respect to polarization of light incident to the reflector prior to the reflection. The Faraday rotator in front of each reflector may be a 45-degree Faraday rotator which rotates the polarization by 45 degrees in a single pass. Hence, each beam coupled into the fiber 111 or 112 is reflected back by the Faraday reflector as a reflected signal beam with a polarization orthogonal to the input polarization prior to the reflection. Under this configuration, the device 100 is insensitive to the polarization variation.

[0013] A variable optical attenuator 130 may be implemented in one of the fibers 111 and 112 such as the fiber 111 as illustrated, or in both of them, to allow for adjustment of the relative power levels in the two fibers 111 and 112. In general, it may be desirable to have equal power levels in the

fibers 111 and 112 to achieve a high contrast in the interference pattern in the output light in the fiber 150. The attenuator 130 may be adjustable either manually or automatically in response to a control signal 132. In addition, at least one of the fibers 111 and 112, such as the fiber 112 as illustrated, may be engaged to a fiber control device 120 to adjust the relative difference of the optical path lengths of the fibers 111 and 112 to optimize interference effect at the output in the fiber 150. The device 122 may be a fiber stretcher or a temperature controller, and may operate to change the optical path length in a fiber in response to a control signal 122.

**[0014]** An optical detector 160, such as a photodiode, may be coupled to the fiber 150 to receive the output light beam to produce a detector output. An analog-to-digital converter (ADC) 170 may be used to convert the detector output from the analog form into a digital signal. Next, a fast Fourier transform (FFT) device 180, which may include a microprocessor, is coupled to the ADC 170 to process the signal and to produce the spectral information of the input light in the fiber 101.

**[0015]** The device 100 may further include a power calibration mechanism to account for any variation in the input power in the fiber 101 during the measurement. As illustrated in FIG. 1, a fiber coupler 102 may be coupled in the fiber 101 to split a

fraction of input light into an optical detector 190 that monitors the variation in the input power. The output 192 of the detector 190 may be fed to the FFT device 180 for calibrating the effects caused by the power variation.

**[0016]** The following describes one exemplary and simplified analytical explanation of the spectrum monitoring mechanism of the device 100. It is understood that other explanations may also be made. For simplicity, it is assumed that the input field for the input beam to the fiber 101 may be written as:

$$E_{in}(t) = E_i A(t) e^{i\omega t} .$$

After the coupling by the coupler 104 with a power-splitting ratio of $\alpha_1/\alpha_2$, two beams are generated in the fibers 111 and 112:

$$E_2 = \frac{\sqrt{\alpha_1 E_o}}{\sqrt{2}} A(t) e^{i\omega t} , \text{ and}$$

$$E_3 = \frac{\sqrt{\alpha_2 E_o}}{\sqrt{2}} A(t) e^{i\omega t} .$$

After reflecting back from the Faraday reflectors 141 and 142, the two reflected beams may be expressed as:

$$E_2'(t) = \frac{\sqrt{T}\sqrt{\alpha_1}E_o}{\sqrt{2}}A(t)e^{i\omega t}\text{, and}$$

$$E_3'(t) = \frac{\sqrt{\alpha_2}E_1}{\sqrt{2}}A(t-\tau)e^{i\omega(t-\tau)},$$

where T is the power attenuation factor of the adjustable optical attenuator 130 in the fiber 111, and $\tau$ is the relative delay between the two arms, i.e., the fibers 111 and 112. The output electric field at the output port of the coupler 110 that connects to the output fiber 150 may be written as:

$$E_4(t) = \frac{\sqrt{\alpha_1}}{\sqrt{2}}E_2'(t) + \frac{\sqrt{\alpha_2}}{\sqrt{2}}E_3'(t) = \frac{E_0}{2}\left[\sqrt{T}\alpha_1 A(t)e^{i\omega t} + \alpha_2 A(t-\tau)e^{i\omega(t-\tau)}\right].$$

The corresponding power in the output fiber 150 is:

$$\begin{aligned}
P_o &= \overline{|E_4(t)|^2} = \frac{E_0^2}{4}\overline{\left|\sqrt{T}\alpha_1 A(t)e^{i\omega t} + \alpha_2 A(t-\tau)e^{i\omega(t-\tau)}\right|^2} \\
&= \frac{E_0^2}{4}\left[T\alpha_1^2\overline{A^2(t)} + \alpha_2^2\overline{A^2(t-\tau)} + 2\sqrt{T}\alpha_1\alpha_2\cos(\omega\tau)\overline{A(t)A(t-\tau)}\right] \\
&= \frac{E_0^2}{4}\left[T\alpha_1^2 + \alpha_2^2 + 2\sqrt{T}\alpha_1\alpha_2\overline{A(t)A(t-\tau)}\cos(\omega\tau)\right],
\end{aligned}$$

wherein the last expression is obtained under the following assumption:

$$\overline{A^2(t)} = \overline{A^2(t-\tau)} = 1.$$

Notice that the cross-term represents the interference between the light beams in the two fiber arms 111 and 112 and is processed to extract spectral information in the input light in the fiber 101.

**[0017]** Next, the FFT results of the output in the fiber 150 is computed. Initially, the following relationship is defined:

$$\overline{A(t)A(t-\tau)} = \int_{-\infty}^{+\infty} A(t)A(t-\tau)e^{-i\omega t}dt \ .$$

The FFT operation is then given by:

$$\text{FFT} = F\left[\overline{A(t)A(t-\tau)}\right] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(t)A(t-\tau)e^{i\omega\tau}d\tau dt \ , \text{ and}$$

$$F(\omega) = F\left[\overline{A(t)A(t-\tau)}\right] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(t)A(t-\tau)e^{i\omega t}dtd\tau \ .$$

Assuming the coupler 110 and the attenuator 130 are configured to satisfy $\sqrt{T}\alpha_1 = \alpha_2 = \alpha$, the following expression for the power can be obtained:

$$P_0 = \frac{E_0^2\alpha^2}{2}\left[1 + \overline{A(t)A(t-\tau)}\cos\omega\tau\right].$$

This power signal is then processed by the FFT device 180 to obtain the spectral information of the input signal.

**[0018]** For a signal with a noise background of $\delta E_0$, the signal can be represented by:

$$E_{in}(t) = E_0\left[A(t)e^{iwt} + \delta\right].$$

The corresponding output power in the fiber 150 is

$$P_0 = \frac{E_0^2\alpha^2}{2}\left[1 + \delta^2 + \overline{A(t)A(t-\tau)}\cos\omega\tau\right].$$

Hence, it is evident that the background noise can reduce the visibility of the interferometer.

**[0019]** If more than one channels are input to the device 100 in FIG. 1, the signals may be expressed as follows for the example of two channels at frequencies $\omega_1$ and $\omega_2$, respectively:

$$E_{in}(t) = E_1 A_1(t)e^{i\omega_1 t + \delta_1(t)} + E_2 A_2(t)e^{i\omega_2 t + \delta_2(t)},$$

where $\delta_1(t)$ and $\delta_2(t)$ represent their different phases. Accordingly, the signals may be written as follows:

$$E_2'(t)=\frac{\alpha}{\sqrt{2}}\left[E_1A_1(t)e^{i\omega_1 t+\delta_1(t)}+E_2A_2(t)e^{i\omega_2 t+\delta_2(t)}\right];$$

$$E_3'(t)=\frac{\alpha}{\sqrt{2}}\left[E_1A_1(t-\tau)e^{i\omega_1(t-\tau)+\delta_1(t-\tau)}+E_2A_2(t-\tau)e^{i\omega_2(t-\tau)+\delta_2(t-\tau)}\right];\ \text{and}$$

$$E_4(t)=\frac{\alpha}{2}\left[E_1A_1(t)e^{i\omega_1 t+\delta_1(t)}+E_1A_1(t-\tau)e^{i\omega_1(t-\tau)\delta_1(t-\tau)}+E_2A_2(t)e^{i\omega_2 t+\delta_2(t)}+E_2A_2(t-\tau)e^{i\omega_2(t-\tau)\delta_2(t-\tau)}\right]$$

The power of the output beam can be represented by the following:

$$|E_4(t)|^2=\frac{\alpha^2}{2}\left[E_1^2+E_1^2A_1(t)A_1(t-\tau)\mathrm{Re}\left[e^{i\omega_1\tau+i\delta_1(t)-i\delta_1(t-\tau)}\right]+E_2^2+E_2^2A_2(t)A_2(t-\tau)\mathrm{Re}\left[e^{i\omega_2\tau+i\delta_2(t-\tau)}\right]\right].$$

This signal is fed into the FFT device 180 to extract the spectral information of the input light. The above equation indicates that the spectral resolution of the device 100 is a function of the maximum value of the relative delays between two fiber arms 111 and 112, $\tau_{max}$, which is inversely proportional to the linewidth $\Delta\nu$ of the input light:

$$\tau_{\max}\propto\frac{1}{\Delta\nu}\quad .$$

As an example, if the maximum relative delay is 100 ps, the maximum linewidth of the input light is about 10 GHz.

**[0020]** FIG. 2 illustrates an exemplary implementation of a spectral monitoring device based on the design in FIG. 1. An electronic control circuit is used to receive the output signals from the detectors 190 and the FFT device 180 to generate the control signal 122 for tuning the relative delay between the two fiber arms 111 and 112. The tuning of the relative delay and the FFT processing are synchronized to generate the spectral information for monitoring. Two signal amplifiers may be used to amplify the detector signals from the two detectors 190 and 160.

**[0021]** The above spectral monitoring devices and technique provide a simple and reliable device design at low cost and yet allow for real-time, high-resolution spectral monitoring operation. Such devices may be implemented with fiber-based designs which can be used for easy deployment in fiber optical systems. In addition, the devices based on the above designs may be packaged in a compact and robust configuration to allow for ease and convenience for diversified applications.

**[0022]** Only a few implementations are disclosed. However, it is understood that variations and enhancements may be made without departing from the spirit of and are intended to be encompassed by the following claims.